THE JOURNAL OF INDONESIA SUSTAINABLE DEVELOPMENT PLANNING

VOL. 7 NO. 1 – APRIL 2026

E-ISSN: 2722-0842 | P-ISSN: 2721-8309

Available online at
http://journal.pusbindiklatren.bappenas.go.id/

Research Paper

Thermochemical-Mechanical Assessment of Washed and Torrefied Biomass Co-Firing in Boilers for a Sustainable Energy Transition

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Abstract

Despite extensive research on biomass co-firing, gaps remain regarding the combined effects of washing, torrefaction, and analytical indices on emission reduction, slagging, and fouling for heterogeneous Indonesian biomass. This study demonstrates that pre-treatment enhances energy density, improves HHV, and imparts coal-like combustion characteristics, reducing CO_2 by up to 12% and SO_2 by up to 30%, while NO_x remains fuel-dependent. Washing lowers alkali metals, mitigating slagging and fouling, and torrefaction stabilizes biomass thermally, improving operational reliability. Findings highlight the CO_2-NO_x trade-off, guiding biomass blend selection and combustion management. This research provides actionable insights for policymakers and energy stakeholders, supporting Indonesia's renewable energy transition, SDGs, and a scalable pathway toward carbon neutrality by 2060.

Keywords: Biomass Co-Firing; Washing; Torrefaction; Emission Mitigation; Carbon-Neutral Energy

ARTICLE INFO
Received: October 14, 2025
Received in revised form:
January 15, 2025
Accepted: April 30, 2026

doi: 10.46456/jisdep.v7i1.1010

THE JOURNAL OF INDONESIA SUSTAINABLE DEVELOPMENT PLANNING
Published by Centre for Planners' Development, Education, and Training (Pusbindiklatren), Ministry of National Development Planning/National Development Planning Agency (Bappenas), Republic of Indonesia

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Supported by Indonesian Development Planners Association (PPPI)

Please cite this article in APA Style as:
Prayitno, H., Rustamaji, H., Arafat, Y., Amrul, & Prabowo, A. D. (2026). Thermochemical-Mechanical Assessment of Washed and Torrefied Biomass Co-Firing in Boilers for a Sustainable Energy Transition. *The Journal of Indonesia Sustainable Development Planning, Vol 7(1),* 99-116. https://doi.org/10.46456/jisdep.v7i1.1010

1. Introduction

The global energy transition has intensified efforts to reduce greenhouse gas emissions while maintaining energy security and system reliability. In coal-dependent economies such as Indonesia, the transition towards fully renewable energy systems remains constrained by infrastructure readiness, investment capacity, and grid stability considerations. Within this context, biomass co-firing, defined as the partial substitution of coal with biomass in existing coal-fired power plants, has emerged as a pragmatic strategy to increase renewable energy penetration while utilizing existing generation assets (Budiarto et al. 2024; Prayitno et al. 2024; Sugiyono et al. 2022).

Despite its potential, the utilization of raw biomass presents technical limitations, including high moisture content, low energy density, heterogeneous composition, and unfavorable ash chemistry, particularly elevated concentrations of alkali metals. These characteristics can reduce combustion stability and increase slagging and fouling risks in coal-based systems (Ghazidin et al. 2024; Putra et al. 2024). In Indonesia, these challenges are compounded by the diversity of biomass residues and decentralized supply chains, which hinder fuel quality standardization and large-scale deployment (Amarachi Queen Olufemi-Phillips et al. 2024; Gunawan, Suryobuwono, and Sholihah 2025; Lestari et al. 2022; Zakia and Sunitiyoso 2025).

Biomass pretreatment has therefore been widely explored to improve fuel quality. Washing reduces ash content and alkali metals, while torrefaction enhances energy density and produces coal-like characteristics (Assureira 2025; Azarpour, Zendehboudi, and Saady 2025; Cahyo et al. 2024; Liu et al. 2024; Ünyay et al. 2023; Yang et al. 2024). However, existing studies predominantly examine these approaches separately, limiting their applicability for practical co-firing systems.

A clear research gap remains. Previous studies have not systematically integrated fuel upgrading through combined washing and torrefaction with ash-related operational risks, particularly slagging and fouling, alongside emission estimation within a single analytical framework. Furthermore, there is a lack of empirical evidence that reflects the characteristics of Indonesian biomass, which are highly variable and critical for real-world implementation. This limitation reduces the relevance of existing findings for operational decision-making and energy policy development.

Based on these gaps, this study aims to evaluate the combined effects of biomass pretreatment, specifically washing and torrefaction, on Indonesian biomass residues when co-fired with low-rank coal. The study examines changes in fuel properties, assesses ash-related operational risks, and estimates emission characteristics under representative co-firing conditions, providing an integrated evaluation of technical feasibility.

This research contributes by delivering Indonesia-specific evidence on biomass pretreatment for co-firing, while integrating fuel characteristics, ash behavior, and emission-related indicators within a coherent analytical framework. The findings provide practical insights for energy planning and support the role of biomass co-firing as a transitional pathway in coal-based systems.

The study is also aligned with sustainable development objectives. The use of biomass residues supports Sustainable Development Goal 7 through increased renewable energy utilization and contributes to Sustainable Development Goal 13 through emission reduction. The valorization of biomass waste advances Sustainable Development Goal 12, while the use of non-food biomass supports Sustainable Development Goal 2. In addition, the development of biomass-based energy systems can promote economic activity and employment, contributing to Sustainable Development Goal 8 (Harahap 2021; Raman and Sreenivasan 2025).

2. Methods

This study aims to evaluate the effects of biomass pretreatment through washing and torrefaction on combustion characteristics, slagging and fouling propensity, and emission estimation in co-firing applications with low rank coal. A mixed-method research design was adopted, integrating controlled laboratory experiments with secondary data-driven analytical approaches. Laboratory experiments were conducted to quantify changes in biomass fuel properties following pretreatment, while secondary datasets were employed for elemental composition analysis, slagging and fouling index calculations, and stoichiometric-based emission estimation. This integrated approach enhances both the analytical rigor and reproducibility of the study.

2.1. Research Design

The methodology combines experimental testing with analytical modeling. Experimental procedures were performed to evaluate variations in higher heating value (HHV) and proximate composition of biomass after washing and torrefaction. Subsequent analyses utilized secondary data to determine elemental composition, calculate slagging and fouling indices, and estimate gaseous emissions under co-firing scenarios with low-rank coal (Chae et al. 2021; Putra et al. 2024).

2.2. Biomass Selection and Sampling

The selected biomass feedstocks include cocoa shells, mangosteen peels, and wood sawdust, chosen based on their regional availability in Indonesia and their relevance to the co-firing supply chain. Samples were obtained from local producers in the Bandar Lampung region.

Prior to treatment, all biomass samples were air-dried to reduce initial moisture content. The dried materials were subsequently milled using a mechanical grinder to obtain a uniform particle size distribution. This preprocessing step was essential to minimize experimental variability and to ensure consistency across calorimetric and proximate analyses (Lin et al. 2021; Ünyay et al. 2023).

2.3. Biomass Washing Procedure

The washing process was conducted to reduce ash content and remove alkali metals, particularly potassium (K) and sodium (Na), which are known to promote deposit formation and increase slagging and fouling risks in combustion systems.

Washing was performed by immersing the biomass in distilled water at a biomass-to-water ratio of 1:10. The process was carried out for 4 hours at ambient temperature (~27°C). To enhance the dissolution and removal of water-soluble inorganic compounds, continuous agitation was applied using a magnetic stirrer at a constant rotational speed.

Following washing, the biomass was filtered and subsequently dried in an oven at 50°C until a constant mass was achieved. This drying step ensured the removal of residual moisture prior to further thermal treatment. The detailed specification of washing parameters is intended to ensure experimental reproducibility.

2.4. Biomass Torrefaction Procedure

Torrefaction was conducted on both washed and untreated biomass samples to enable comparative analysis. The process was performed using a continuous tubular reactor equipped with precise temperature control (figure 1).

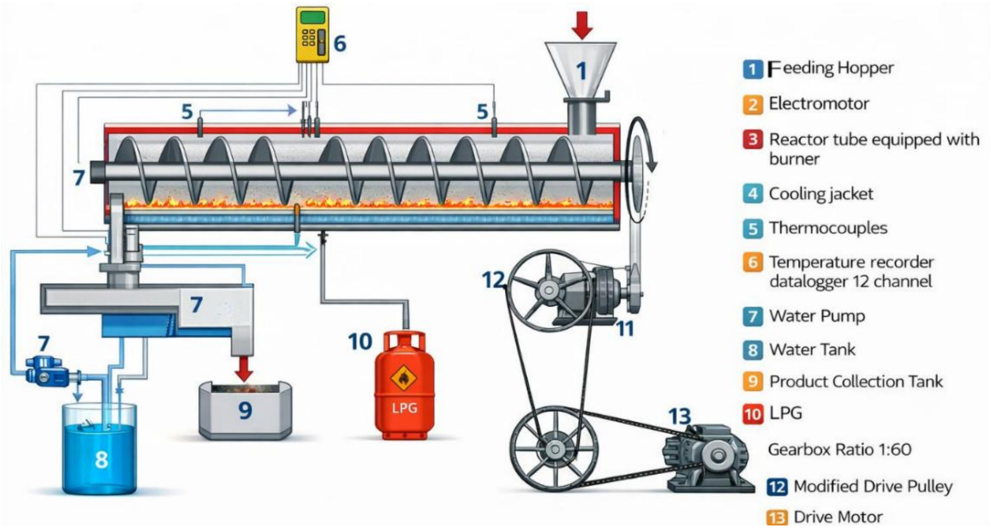

Figure 1. Torrefaction Installation (Amrul et al. 2025; Prayitno et al. 2024).

The torrefaction temperatures were set at 250°C, 275°C, and 300°C, with a fixed residence time of 30 minutes for each condition. The heating rate was maintained at 5°C/min to ensure controlled thermal decomposition (Amrul et al. 2025; Prayitno et al. 2024). The process was carried out under a limited-oxygen (oxygen-deficient) atmosphere to prevent combustion while allowing thermal degradation of biomass components (Mamvura and Danha 2020; Prasongthum et al. 2022; Ünyay et al. 2023).

Each experimental run utilized a sample mass of 500 g to ensure representativeness and consistency of results. Upon completion, the torrefied samples were allowed to cool naturally under ambient conditions to minimize oxidation prior to subsequent analyses. These detailed operational parameters are provided to facilitate reproducibility by other researchers.

2.5. Higher Heating Value (HHV) Determination

The higher heating value (HHV) of untreated, washed, and torrefied biomass samples was determined using an Oxygen Bomb Calorimeter (BK-1A+) as shown in Figure 2, following ASTM D240-14. The measurement involved complete combustion of the sample in a high-pressure oxygen environment, with the resulting temperature rise used to quantify the released energy. HHV values were calculated based on the recorded temperature change and sample mass. All measurements were conducted in triplicate to ensure the reliability and reproducibility of the experimental results.

Figure 2. Oxygen Bomb Calorimeter BK-1A+ (Amrul et al. 2025)

2.6. Proximate Analysis

Proximate analysis was conducted to determine moisture content, volatile matter, ash content, and fixed carbon. The procedures followed ASTM D3173 (moisture), ASTM D3174 (ash), and ASTM D3175 (volatile matter). Fixed carbon was calculated by difference. The results were used to assess changes in combustion-related properties due to washing and torrefaction treatments.

2.7. Ultimate Analysis

Ultimate analysis was performed using secondary data obtained from relevant literature sources to determine the elemental composition (C, H, N, S, and O) of both biomass and coal. These data were used to calculate atomic H/C and O/C ratios for Van Krevelen analysis and served as the basis for theoretical emission estimations (Chen et al. 2021).

2.8. Slagging and Fouling Indices

Slagging and fouling indices were employed to assess the potential for deposit formation in biomass combustion systems. The calculations were carried out using the base-to-acid ratio, the slagging index, and the fouling index. These indices were determined based on the oxide composition of the biomass ash. The resulting values were classified into low, moderate, and high categories for each parameter, indicating the likelihood of slag and fouling formation within the boiler (Assureira 2025; Lachman et al. 2021; Putra et al. 2024; Suyatno et al. 2024).

Formulation for the calculations:

Table 1: Slagging and Fouling Risk Classification Based on Ash Composition

Parameter	**Formula**	**Low (Risk)**	**Medium (Risk)**	**High (Risk)**	**Eq.**
Basic-Acidic Ratio **(B/A)**	$^{B}/_{A} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$	<0.206	0.206–0.4	>0.4	(1)
Slag Viscosity Index **(Sr)**	$S_r = \frac{SiO_2}{SiO_2 + aO + MgO + Fe_2O_3}$	>72	65–72	<65	(2)
Slagging Index **(Rs)**	$R_s = \left(^{B}/_{A}\right) x\, S$	<0.6	0.6–2.0	>2.0	(3)
Fe/Ca Ratio **(RFe/Ca)**	$^{RFe}/_{Ca} = \frac{Fe_2O_3}{CaO}$	<8	8–15	>15	(4)
Fouling Index **(Sf)**	$Sf = \left(^{B}/_{A}\right) x\, (Na_2O + K_2O)$	<1.2	1.2–2.5	>2.5	(5)

Slagging and fouling indices were employed to assess the potential for deposit formation in biomass combustion systems. The calculations were carried out using the base-to-acid ratio, the slagging index, and the fouling index. These indices were determined based on the oxide composition of the biomass ash. The resulting values were classified into low, moderate, and high categories for each parameter, indicating the likelihood of slag and fouling formation within the boiler. This approach enables a comparative evaluation of operational risks associated with different biomass samples under co-firing conditions (Putra et al. 2024; Suyatno et al. 2024).

2.9. Emission Estimation and Combustion Indicators

The estimation of CO_2, SO_2, and NO_x emissions was performed using stoichiometric combustion equations based on the ultimate analysis of biomass and low rank coal. The assumptions of complete combustion and 20% excess air were applied, with all nitrogen (N) converted to NO_2, treated as NO_x equivalent (Simona, Serban, and Paraschiv 2020).

CO_2 emissions were calculated using the following formula:

$$\text{Emissions of } CO_2 = \frac{\text{C (Co−Firing)}\times 44}{12} \tag{6}$$

SO_2 emissions were derived from the sulphur content using:

$$\text{Emissions of } SO_2 = \frac{\text{S (Co−Firing)}\times 64}{32} \tag{7}$$

NO_x emissions were estimated assuming all nitrogen in the fuel converts to NO_2, calculated by:

$$\text{Emissions of } N_2 = \frac{\text{N (Co−Firing)}\times 46}{14} \tag{8}$$

The impact of 20% excess air was considered by adjusting the CO_2 emissions, multiplying the total by a factor of 1.20. These calculations provide a theoretical estimate of emissions for a co-firing scenario involving biomass and low-rank coal.

3. Results and Discussions

3.1 Biomass in Indonesia's Energy Transition Agenda

Within Indonesia's energy transition agenda, biomass has emerged as a prominent renewable energy source, receiving substantial legal and policy legitimacy following the enactment of Law No. 30/2007 on Energy. Further elaboration under Government Regulation No. 40/2025 on the National Energy Policy (KEN) directs the utilization of biomass towards the partial substitution of coal in power generation and the production of biogas for the transport and industrial sectors, with projected demand reaching approximately 67.5–71.9 MTOE (million tons of oil equivalent) by 2060. At this level, biomass is expected to contribute approximately 12.2–13.4% of the national energy mix. Operationally, these policy directions have been reinforced through sectoral regulations of the Ministry of Energy and Mineral Resources (MEMR), notably No. 12/2023 on the Utilization of Biomass Fuel as a fuel mixture in steam power plants (PLTU) and MEMR Regulation No. 10/2025 on the Energy Transition Roadmap for the Electricity Sector.

Table 2: Regulation Framework Related to Biomass as a Part of Energy Transition

No	Regulation	Policy Focus on Biomass Energy
1	Law No. 30/2007 on Energy	Provides legal recognition of biomass as a part of renewable energy and promotes its role in energy diversification in alignment with the principles of energy security and sustainability.
2	Government Regulation (PP) No. 40/2025 on National Energy Policy (KEN)	Sets the strategic direction, projections, and optimization pathways for the role of biomass in the national energy mix, including development targets, bioenergy diversification, and the substitution of coal with biomass.
3	Presidential Regulation No. 12/2025 on RPJMN 2025–2029	Positions the strengthening of new and renewable energy and energy self-sufficiency *(swasembada energi)* as key development priorities in 2025–2029 National Medium-Term Development Plan (RPJMN). Moreover, biomass is an integral component of the green energy and energy security agenda.
4	MEMR Regulation No. 12/2023 on Utilization of Biomass Fuel as a Fuel Mixture in Steam Power Plants (PLTU)	Establishes the regulatory procedures governing the utilization of biomass as a co-firing feedstock in coal-fired power plants (PLTU) and underscores the imperative to incorporate sustainability and environmental safeguards in its implementation.
5	MEMR Regulation No. 10/2025 on Energy Transition Roadmap for the Electricity Sector	Establishes biomass cofiring as a key transition instrument for coal-fired power plants (PLTU), positioning it within the broader emissions reduction package for the electricity sector.

From a national development perspective, biomass supports the energy self-sufficiency priorities of President Prabowo's administration, particularly in advancing the adoption of clean energy. As of 2025, the share of renewable energy remains relatively modest, at around 15.75%, highlighting the need for accelerated deployment (MEMR, 2026). In this context, the National Medium-Term Development Plan (RPJMN) 2025–2029 sets a more ambitious target of achieving a 23% share of renewable energy in the national energy mix by 2029, positioning biomass as a complementary transition resource, alongside other renewable technologies (Bappenas, 2025). Table 1 illustrates the position and role of biomass within Indonesia's energy transition agenda. These regulatory instruments collectively demonstrate the government's commitment to advancing the energy transition while simultaneously reducing greenhouse gas emissions. Building on this policy framework, the technical performance of biomass becomes a critical determinant of its practical viability in supporting large-scale co-firing implementation. In this regard, pre-treatment processes, such as washing and torrefaction, play an essential role in improving fuel quality and ensuring compatibility with existing coal-fired boiler systems.

3.2 Impact of Biomass Washing on Calorific Value

The biomass washing process has proven to be exceptionally effective in enhancing combustion quality by reducing alkali metals and ash content, which are major contributors to slagging and fouling in coal-fired power plant boilers. This washing process resulted in a significant increase in higher heating value (HHV) across all tested biomass samples, as shown in Table 2. For instance, cocoa shells exhibited an increase in HHV from 17.74 MJ/kg (raw) to 27.89 MJ/kg after washing. This increase in calorific value can be attributed to the removal of non-combustible materials, such as ash and other inorganic compounds, which otherwise diminish energy efficiency during combustion. These findings are consistent with those of Ghazidin et al. (2024), who also observed a similar increase in calorific value following the washing of biomass.

The increase in calorific value following washing not only enhances combustion efficiency but also reduces the amount of biomass required to produce the same energy output. This provides significant economic advantages, as it lowers fuel costs and improves the competitiveness of biomass as a renewable energy source. Furthermore, by decreasing the concentration of alkali metals in the biomass, the washing process helps to mitigate the risks of slagging and fouling, which are often problematic in biomass co-firing systems with coal. The reduction in alkali metals such as potassium (K) and sodium (Na) is crucial for maintaining operational stability and reducing the need for costly boiler maintenance. These findings are further corroborated by Putra et al. (2024), who demonstrated that washing significantly.

Table 3: Calorific Value Testing Results of Various Wood Types

No	Biomass Type	Dry Mass (g)	Calorific Value (J/g)	kcal/kg	Wet Mass (g)	Calorific Value (J/g)	kcal/kg
1	White Wood	0.62	16280	3890.92	0.48	18170	4342.63
2	Mahogany	0.72	18046	4312.99	0.53	18251	4361.99
3	Teak	0.60	19473	4654.05	0.40	20744	4957.82
4	Champaca	0.40	18315	4377.29	0.33	22270	5322.53
5	Bayur	0.54	18212	4352.67	0.43	18423	4403.10

No	Biomass Type	Dry Mass (g)	Calorific Value (J/g)	kcal/kg	Wet Mass (g)	Calorific Value (J/g)	kcal/kg
6	Sandalwood	0.29	19913	4759.21	0.35	18874	4510.89
7	Acacia	0.34	16898	4038.62	0.32	18787	4490.09
8	Kenam	0.52	19754	4721.21	0.68	19879	4751.08
9	Alaban	0.83	18281	4369.16	0.50	18875	4511.13
10	Damar	0.94	18281	4369.16	0.80	18690	4466.91
11	Merbau	1.05	20132	4811.55	1.00	20452	4888.03

3.3 Influence of Torrefaction on Biomass Fuel Properties

3.2.1 Energy Densification and Coal-like Characteristics

The torrefaction process has proven to be an exceptionally effective method for enhancing biomass energy density, making it more compatible for co-firing with low-rank coal. As demonstrated in Figure 3 and Table 3, torrefaction results in a significant increase in the calorific value (CV) of biomass. For instance, cocoa shells increased from 17.74 MJ/kg (raw) to 27.89 MJ/kg at 275°C, indicating that torrefaction enhances the energy content of biomass by reducing volatile matter and moisture. This improvement aligns with the findings of Prayitno et al. (2024), who also observed a significant increase in the energy density of biomass following torrefaction.

Torrefaction transforms biomass into a more stable fuel with coal-like characteristics, which is critical for the co-firing process with coal. As shown in Figure 3, torrefaction results in a reduction in the H/C and O/C ratios, indicating a shift towards coal-like properties, which significantly enhances combustion stability and reduces emissions. This reduction in ratios is particularly important, as it enables biomass to be more easily integrated into coal-based combustion systems without compromising operational performance. These findings are supported by Ünyay et al. (2023), who concluded that torrefied biomass is more compatible with coal combustion systems, making it more stable and better suited for integration into coal-based combustion processes.

3.2.2 Changes in Proximate Composition

The proximate analysis presented in Table 3 demonstrates pronounced transformations in moisture content (MC), volatile matter (VM), and fixed carbon (FC) following torrefaction. These trends are in close agreement with the established theoretical framework of torrefaction, whereby the progressive devolatilization of biomass leads to an enrichment of fixed carbon, thereby enhancing the overall energy density of the material. For instance, cocoa shells exhibit a substantial decline in volatile matter, decreasing from 72.71% in the raw biomass to 51.78% at 275°C, while fixed carbon increases markedly from 1.19% to 29.87%. This observation substantiates the principle that torrefaction effectively concentrates energy by eliminating low-energy volatile fractions, yielding a carbon-enriched fuel with improved thermal stability and combustion performance (Ünyay et al. 2023).

The concurrent reduction in volatile matter and enrichment of fixed carbons are of critical importance, as excessive volatile components are often associated with incomplete combustion, elevated emissions, and operational instability. Through the mitigation of unburned hydrocarbons and carbon monoxide (CO) formation, torrefaction enhances combustion efficiency and promotes more stable thermal behavior. Consequently, the observed increase in calorific value (CV), coupled with improved fuel stability, renders torrefied biomass a more suitable and reliable candidate for co-firing applications with low-rank coal (Basu, P., & Kaushal 2024; Tumuluru et al. 2021).

Table 4: Proximate Analysis

Biomass	Torrefied	CV (cal/g)	CV (MJ/kg)	MC (wt%)	VC (wt%)	FC (wt%)	Ash (wt%)
Coffee Husk	Raw	4495.63	18.82	8.91	74.64	9.31	7.13
	250°C	6298.90	26.37	1.56	54.50	30.11	13.84
	275°C	6519.28	27.29	1.35	47.95	35.98	14.72
	300°C	6115.80	25.61	0.41	34.34	35.66	29.58
Cocoa Shell	Raw	4236.50	17.74	15.22	72.71	1.19	10.88
	250°C	5083.28	21.28	1.56	67.35	20.09	11.00
	275°C	6661.58	27.89	0.11	51.78	29.87	18.24
	300°C	6277.34	26.28	0.07	44.92	32.63	22.38
Mangosteen Shell	Raw	5656.00	23.68	12.32	73.45	12.11	2.12
	250°C	6392.66	26.76	0.39	72.57	23.10	3.94
	275°C	6805.00	28.49	0.26	69.69	24.28	5.77
	300°C	6875.60	28.79	0.13	63.67	28.97	7.23

Biomass	Torrefied	CV (cal/g)	CV (MJ/kg)	MC (wt%)	VC (wt%)	FC (wt%)	Ash (wt%)
Rubber Wood (Kongto et al. 2021)	Raw	4727.53	19.78	4.60	81.80	16.60	1.61
	200°C	4854.21	20.31	1.07	80.36	17.94	1.70
	250°C	5298.76	22.17	0.88	71.08	26.74	2.18
	300°C	6493.78	27.17	0.73	43.75	52.42	3.83
Mahogany Wood (Suyatno et al. 2023)	**Raw**	4278.00	17.90	8.01	67.35	16.79	7.85
Teak Wood Char	750°C	6575.05	27.51	2.12	17.88	69.11	10.89
Acacia Wood (Suyatno et al. 2023)	**Raw**	3831.00	16.03	8.21	60.92	14.90	15.97
Low Rank Coal (Suyatno et al. 2023)	**Raw**	6626.00	27.72	10.14	39.86	43.38	6.62
O-SCS (Assureira 2025)		4158.70	17.40	-	75.10	15.80	9.10
W-SCS (Assureira 2025)		4397.70	18.40	-	81.80	12.60	5.60

In the case of sugarcane straw, distinct differences are observed between untreated and washed samples. While O-SCS (sugarcane straw before leaching) exhibits a comparatively higher volatile matter content than W-SCS, it nevertheless derives significant benefits from torrefaction, particularly in terms of increased fixed carbon and enhanced post-treatment energy density. O-SCS, with a volatile matter content of 75.10%, indicates considerable potential for improvement in combustion stability and energy yield upon thermal upgrading. In contrast, W-SCS, despite its relatively high volatile fraction (81.80%), possesses lower ash content, which contributes to inherently improved combustion stability and a reduced propensity for slagging and fouling phenomena. However, similar to O-SCS, torrefaction remains essential to elevate its energy density to levels compatible with co-firing requirements (Assureira, 2025).

3.2.3 Elemental Enhancement and Combustion Implications

The ultimate analysis presented in Table 4 reveals significant alterations in the elemental composition of biomass following torrefaction. The dataset is derived from the literature on comparable biomass types investigated experimentally in this study, including cocoa shells, mangosteen peels, coffee husks, and washed wood residues subjected to torrefaction in Bandar Lampung. This analysis facilitates a detailed examination of variations in carbon, hydrogen, oxygen, and sulphur contents, thereby enabling a more comprehensive understanding of the combustion behavior of pre-treated biomass.

The pre-treatment stage involving biomass washing is primarily intended to reduce alkali metal and ash content, both of which are known to exacerbate slagging and fouling during combustion. Specifically, the removal of potassium (K) and sodium (Na) mitigates ash-related operational challenges and enhances boiler reliability. In parallel, torrefaction serves to upgrade the fuel quality by reducing moisture and volatile matter while enriching fixed carbon content. Consequently, torrefied biomass exhibits lower O/C and H/C atomic ratios, indicating a progressive shift towards coal-like characteristics (figure 3). This transformation significantly improves the compatibility of biomass with conventional coal-fired systems, thereby enabling higher co-firing ratios and enhanced combustion efficiency.

For instance, in the case of cocoa shells, the ultimate analysis indicates that carbon content increases substantially from 41.94% (raw biomass) to 55.00% at 300°C, while oxygen content decreases markedly from 44.27% to 28.68%. This enrichment of carbon is particularly critical, as it contributes to improved combustion efficiency, reduced oxygen demand, and enhanced energy release during oxidation reactions. Such trends are consistent with the findings of Amrul et al. (2025); Prayitno et al. (2024), who reported notable improvements in the calorific value of torrefied biomass.

Table 5: Ultimate Analysis

Biomass	Torrefied	C (%)	H (%)	N (%)	S (%)	O (%)
Cocoa Shell (Surono et al 2020)	**Raw**	41.94	5.87	0.93	0.16	44.27
	300°C	55.00	4.98	1.04	0.14	28.68
Coffee Husk (Setter et al. 2020)	350°C	69.96	3.63	3.58	0.24	22.58
	400°C	72.94	3.09	3.32	0.11	20.55
	450°C	74.22	2.50	3.06	0.14	20.07
Mangosteen Shell (Evi et al. 2012)	**Raw**	39.10	5.50	1.00	0.03	54.37
	200°C	39.30	5.90	1.00	0.06	53.74

Biomass	Torrefied	C (%)	H (%)	N (%)	S (%)	O (%)
Oil Palm Fronds (Kongto et al. 2022)	**Raw**	57.39	7.65	0.72	-	34.24
	275°C	61.54	1.47	0.50	-	36.49
Rubber Wood (Kongto et al. 2021)	**Raw**	48.67	6.03	0.09	0.11	43.48
	200°C	49.96	6.11	0.12	0.05	42.06
	250°C	55.14	5.85	0.16	0.04	36.63
	300°C	69.41	4.85	0.36	0.05	21.49
Mahogany Wood (Suyatno et al. 2023)	**Raw**	42.83	4.85	0.21	0.01	36.12
Teak Wood Char (Hartoyo and Rachma 2023)	**Raw**	69.57	4.65	0.28	0.31	25.20
Acacia Wood (Suyatno et al. 2023)	**Raw**	38.78	4.70	0.32	0.03	31.33
Low Rank Coal (Suyatno et al. 2025)	**Raw**	62.26	4.62	1.5	0.7	24.3
O-SCS (Assureira 2025)	**Raw**	43.9	5.52	0.33	0.28	40.9
W-SCS (Assureira 2025)	**Raw**	52.2	5.29	0.3	0.12	36.5

Torrefaction effectively transforms biomass into a more stable, coal-like fuel, which is highly advantageous for co-firing applications. The observed reduction in O/C and H/C ratios reflects a transition towards improved combustion stability and lower emission intensity. Biomass with reduced oxygen content exhibits greater compatibility with coal combustion systems, allowing for increased co-firing ratios without compromising operational performance. These findings are in agreement with Azarpour, Zendehboudi, and Saady. (2025), who emphasized the enhanced integration of torrefied biomass within coal-based energy systems.

Overall, the ultimate analysis provides critical insights into the viability of biomass for co-firing applications. The synergistic effects of washing (alkali reduction) and torrefaction (carbon enrichment) result in a fuel with superior energy density and improved combustion characteristics. The decline in O/C and H/C ratios not only enhances the inherent energy content but also reduces oxygen dependency during combustion and minimizes emission formation.

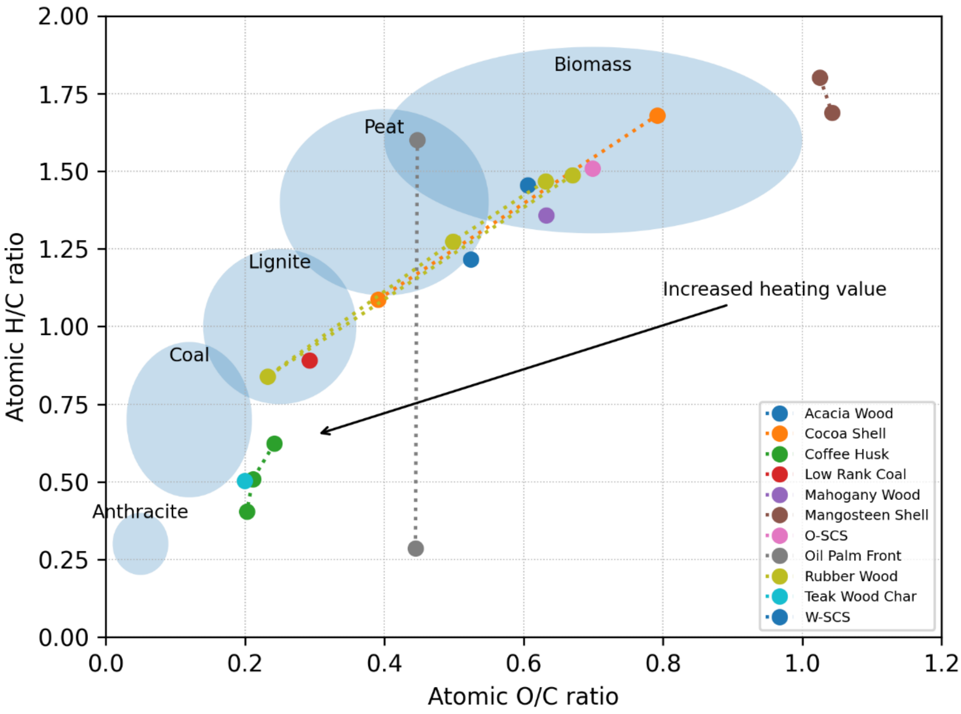

Figure 3. Van Krevelen Diagram

3.2.4 Slagging and Fouling Behavior in Co-Firing Blends

An increase in biomass fraction within co-firing blends is generally associated with an elevated risk of slagging and fouling, primarily due to the higher concentration of alkali metals inherent in the biomass. The results presented in Table 5 demonstrate that higher biomass proportions (e.g., 30%) tend to intensify deposition-related risks, although the extent of this effect is strongly influenced by the specific fuel characteristics. This relationship can be quantified using equations 1–5, which outline the calculation of the B/A ratio, slagging index, and fouling index-all of which show a direct correlation between increased alkali metal content and the potential for slagging and fouling.

For instance, a 20% cocoa husk (CH) blend exhibits a relatively high B/A ratio (2.04), indicating a pronounced fouling propensity. In contrast, the 30% CH blend demonstrates a lower B/A ratio (1.63), suggesting a comparatively reduced fouling tendency, albeit still within a critical range. This behavior implies that alkali metal interactions and ash chemistry, rather than biomass fraction alone, govern deposition tendencies, particularly at intermediate blending ratios.

In the case of washed sugarcane straw (W-SCS), a 20% blending ratio yields a relatively low B/A value (0.81), indicative of limited fouling potential. Upon increasing the biomass fraction to 30%, the B/A ratio decreases slightly to 0.73; however, the fouling tendency remains within a moderate classification. This behavior can be attributed to the effectiveness of the leaching (washing) process, conducted at 80°C for 20 minutes under continuous agitation, which significantly reduces alkali metal content, particularly potassium (K) and sodium (Na) (Assureira, 2025). The removal of these species mitigates slagging and fouling risks, enhances operational reliability, and improves the compatibility of W-SCS with coal-fired combustion systems (Putra et al. 2024).

Table 6: Prediction slagging fouling

No	Biomass Type	B/A	B/A Tendency	Sr	Sr Tendency	Rs	Rs Tendency	Sf	Sf Tendency
1	20% CH	2.04	High	42.6	Low	1.34	Medium	High	High
2	30% CH	1.63	Medium	42.1	Low	1.19	Medium	High	High
3	20% W-SCS	0.81	Low	34.7	Medium	0.9	Low	Medium	Medium
4	30% W-SCS	0.73	Low	35	Medium	0.86	Low	Medium	Medium
5	20% WP	0.19	Low	72	Low	0.19	Low	Low	Low
6	30% WP	0.18	Low	73.2	Low	0.18	Low	Low	Low
7	20% Acacia	0.58	Medium	38.2	Medium	0.58	Low	Medium	Medium

For wood pellets (WP), both 20% and 30% blends exhibit exceptionally low B/A ratios (0.19 and 0.18, respectively), indicating negligible fouling tendencies. This reflects the inherently low alkali metal content of wood pellets, which substantially minimizes ash-related deposition issues, even at higher biomass proportions. These results highlight the robustness of wood pellets as a co-firing fuel in maintaining stable combustion conditions.

In the case of Acacia, a 20% blend presents a moderate B/A ratio (0.58), corresponding to a medium fouling tendency, while a 30% blend shows a slightly reduced B/A value (0.53), with a similar fouling classification. This suggests that, although Acacia contains a moderate level of alkali metals, its behavior remains relatively stable across varying blending ratios, albeit less favorable compared to pre-treated biomass such as W-SCS.

Overall, biomass types characterized by low alkali metal content-such as washed sugarcane straw and wood pellets—demonstrate superior performance in mitigating slagging and fouling during co-firing operations. These findings underscore the critical importance of appropriate pre-treatment strategies, particularly washing, in reducing alkali-related contaminants and ensuring the long-term operational reliability of coal-fired power systems.

3.4 Emission Prediction and Combustion Efficiency Indicators

Leaching and torrefaction significantly influence gaseous emissions (CO_2, SO_2, and NO_x) and combustion efficiency in coal–biomass co-firing systems, with treated biomass consistently demonstrating superior emission reduction performance (Figures 3.2–3.4). Emission estimation was conducted using a stoichiometric approach based on the ultimate analysis of biomass–coal blends, assuming complete combustion with 20% excess air. Calculations follow Eq. (6)–(8), where elemental carbon, sulphur, and nitrogen are converted into CO_2, SO_2, and NO_x, respectively (Chae et al. 2021, 2025).

NO_x emissions are estimated from fuel-bound nitrogen and reported as NO_2-equivalent, a standard convention in emission modelling. While NO typically dominates NO_x formation, this representation ensures regulatory consistency and comparability across studies. Consequently, the results reflect a theoretical upper bound under complete conversion conditions. A correction factor of 1.20 was applied to account for 20% excess air, representing typical industrial boiler operation and its effect on flue gas volume and oxidation conditions.

In the case of W-SCS (washed sugarcane straw), CO_2 emissions decrease markedly following leaching, primarily due to the removal of alkali metals such as potassium (K) and sodium (Na), which are associated with combustion instability and deposition phenomena. A 20% W-SCS + 80% low-rank coal (LRC) blend demonstrates greater CO_2 reduction than an equivalent cocoa husk (CH) blend, reflecting the benefits of alkali removal. Simultaneously, partial sulphur removal during leaching contributes to reduced SO_2 emissions. At a higher blending ratio (30% W-SCS + 70% LRC), CO_2 reduction remains substantial, indicating that pre-treatment enhances fuel reactivity and combustion efficiency by producing a cleaner, more homogeneous fuel matrix requiring less oxygen for complete oxidation.

Torrefaction further improves combustion performance by increasing fixed carbon content and reducing moisture and volatile matter. In both wood pellets (WP) and W-SCS, this results in more stable and efficient combustion conditions. A 20% WP + 80% LRC blend, characterised by a very low B/A ratio (0.19), exhibits minimal fouling and improved combustion efficiency, leading to reduced CO_2 and SO_2 emissions. This trend persists at higher blending ratios (30% WP), confirming the robustness of torrefied wood pellets as a low-emission co-firing fuel.

It should be noted that this approach does not explicitly account for thermal NO_x and prompt NO_x formation mechanisms; therefore, the model primarily reflects fuel NO_x contributions and may not fully capture temperature-dependent nitrogen oxidation pathways in practical combustion systems.

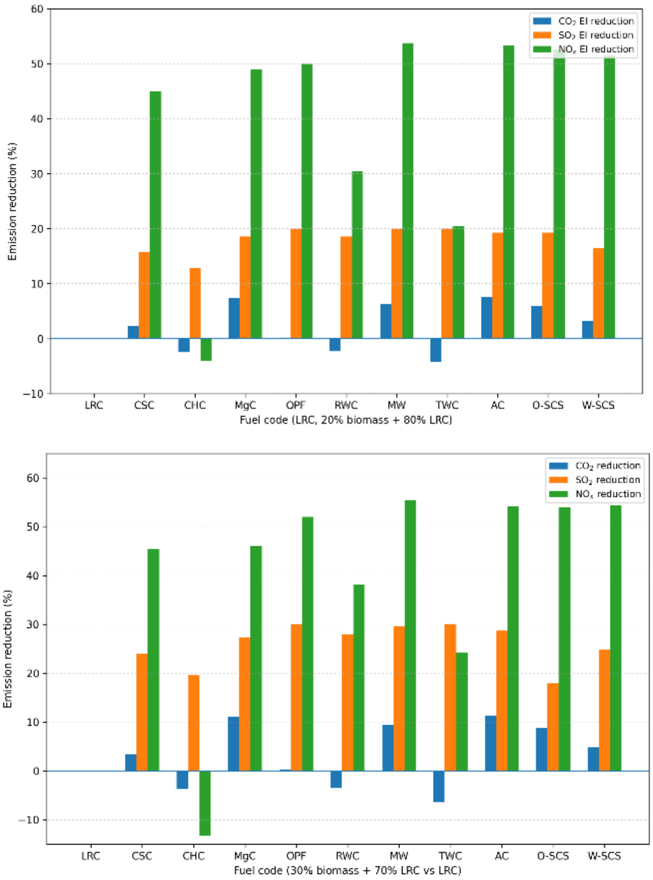

Figure 4. Prediction of CO_2, SO_2, and NO_x Emission Reduction in Biomass-Coal Blends

In contrast, biomass with higher alkali content, such as cocoa husk (CH), presents inherent limitations. Despite torrefaction-induced increases in higher heating value (HHV), a relatively high B/A ratio (2.04) indicates persistent fouling risk and reduced combustion stability. This demonstrates that ash chemistry, rather than energy content alone, governs practical co-firing performance.

NO_x emissions are strongly governed by fuel-bound nitrogen. Biomass types such as coffee husk and mangrove shells, which contain higher nitrogen levels, consistently exhibit elevated NO_x emissions. Pre-treatment processes exert only a limited influence on NO_x reduction, confirming that fuel composition remains the dominant controlling factor.

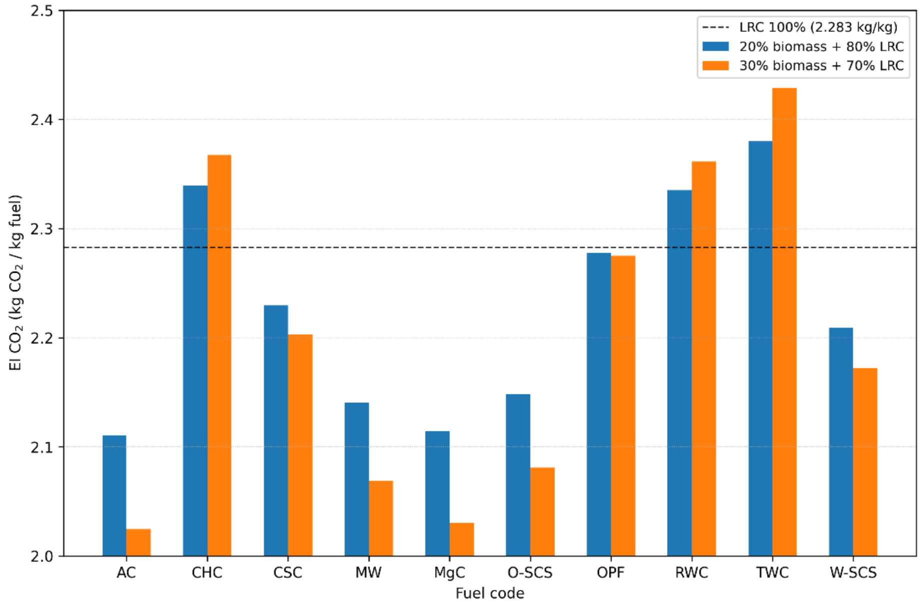

Figure 5. Prediction of CO_2 Emission Profiles in Biomass-Coal Blends

As shown in Figure 5, NO_x emissions remain comparatively high for nitrogen-rich biomass even after torrefaction, reinforcing the limitation of pre-treatment in mitigating fuel-derived NO_x formation. Figure 6 indicates that pre-treated biomass-coal blends exhibit lower Fuel-Air Ratios (FAR), reflecting improved air-fuel mixing and combustion efficiency. Lower FAR values, particularly for W-SCS and wood pellets, are associated with reduced flue gas volume, lower auxiliary energy demand, and decreased CO_2 emissions.

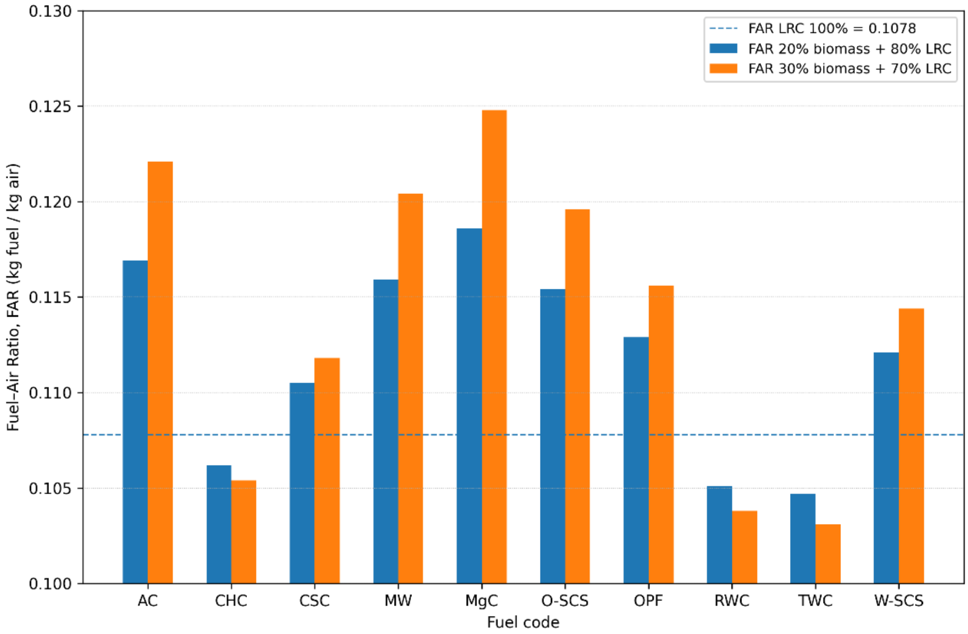

Figure 6. Prediction of Fuel-Air Ratio Profiles in Biomass-Coal Blends

Overall, the combined application of leaching and torrefaction enhances combustion efficiency and reduces emissions in co-firing systems. Leaching mitigates alkali metals and sulphur, reducing slagging, fouling, and SO_2 emissions, while torrefaction improves fuel quality through carbon enrichment and increased energy density. These synergistic effects contribute to improved operational reliability and support the transition towards lower-emission coal-based power generation systems.

However, NO_x emissions remained highly dependent on the nitrogen content of the biomass and the combustion conditions. Biomass types with higher nitrogen content, such as coffee husk and mangrove shells, demonstrated higher NO_x emissions, confirming that these emissions are particularly sensitive to the specific composition of the fuel, as well as the temperature and air-fuel ratio during combustion. Therefore, the findings should be interpreted as comparative screening data, as NO_x emissions vary significantly with operational settings, as indicated in Figure 5.

3.5 Integrated Insights for Sustainable Energy Planning

The findings of this study demonstrate that leaching and torrefaction function as complementary pre-treatment strategies that significantly enhance biomass quality for co-firing applications. Leaching primarily improves ash behavior by reducing alkali metal content, thereby mitigating slagging and fouling tendencies within boiler systems. This reduction not only minimizes deposition-related operational risks but also contributes to improved combustion efficiency, as reflected in the enhanced higher heating value (HHV) of washed biomass.

Conversely, torrefaction provides substantial enhancement in energy density, transforming biomass into a more coal-like fuel in terms of physicochemical and combustion characteristics. This transformation improves thermal stability, handling properties, and combustion consistency, thereby facilitating more reliable integration into co-firing systems. These synergistic effects are clearly illustrated in Figure 7, which presents the optimal performance profiles of various pre-treated biomass types.

The combined benefits of leaching and torrefaction markedly improve the technical viability and fuel consistency of biomass, particularly when derived from heterogeneous residual feedstocks. Such pre-treatment ensures compliance with fuel quality specifications, enhances combustion stability, and reduces operational uncertainty in coal-fired power plants. Accordingly, these strategies enable a more scalable and reliable implementation of biomass co-firing, positioning it as a practical pathway within Indonesia's energy transition framework.

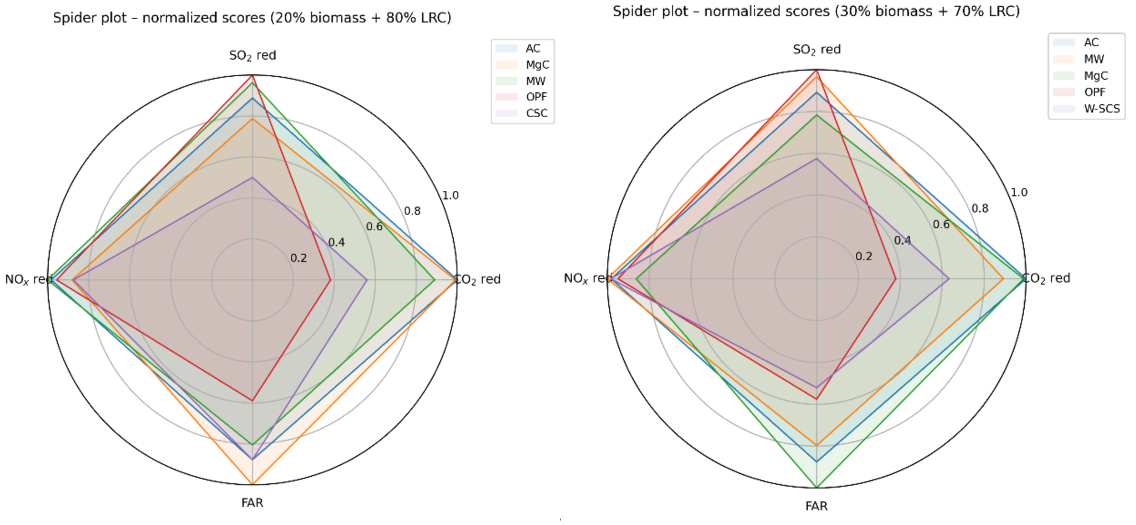

Figure 7. Provides an optimum-analysis co-firing

Figure 7 further illustrates the comparative normalized performance scores of pre-treated biomass (e.g., W-SCS, wood pellets (WP), and cocoa husk (CH)) across co-firing scenarios of 20% biomass + 80% low-rank coal (LRC) and 30% biomass + 70% LRC. Pre-treatment consistently improves compatibility with coal combustion systems, as evidenced by reductions in CO_2 and SO_2 emissions, alongside lower Fuel–Air Ratio (FAR) values indicative of enhanced combustion efficiency.

These findings provide a structured framework for sustainable energy planning in Indonesia. A key strategic implication is the prioritization of biomass pre-treatment at or near the feedstock source to stabilize fuel quality and minimize logistical inefficiencies. Feedstock selection should be guided by critical parameters such as HHV and ash-related indices, ensuring that only suitable biomass is utilized for co-firing applications. Furthermore, the progressive integration of biomass into existing coal-fired power plants should be implemented through staged co-firing ratios, taking into account plant readiness, combustion constraints, and biomass supply chain maturity. This phased approach reduces technical risk while enabling adaptive optimization of co-firing performance.

Overall, this integrated strategy supports energy security, enhances operational reliability, and aligns with Indonesia's national renewable energy targets and decarbonization objectives (Budiarto et al. 2024; Cahyo et al. 2024; Sugiyono et al. 2022; Yudiartono, Windarta, and Adiarso 2023).

3.6 Discussion

The results unequivocally demonstrate that biomass pre-treatment, particularly leaching and torrefaction, substantially enhances combustion characteristics, thereby improving the technical viability of biomass for co-firing with coal. Leaching effectively reduces alkali metal content, directly mitigating slagging and fouling risks, which in turn enhances combustion efficiency and prolongs boiler lifespan by limiting deposit formation. In parallel, torrefaction increases energy density and thermal stability, rendering biomass more coal-like in its combustion behavior. This transformation promotes more complete oxidation, reduces oxygen demand, and contributes to lower emission intensity and improved energy efficiency.

The observed increase in calorific value following torrefaction is primarily attributed to the reduction of moisture and volatile matter, resulting in a more energy-dense fuel. This enhancement is particularly evident in coffee husk and mangrove shells, where increased fixed carbon content improves thermal compatibility with coal and enhances co-firing performance. Such consistency in fuel behavior is critical for large-scale applications, where stable and predictable combustion conditions are essential for operational reliability.

Leaching further contributes to improved combustion performance by significantly reducing alkali metals, particularly potassium (K) and sodium (Na), as observed in W-SCS and wood pellets (WP). This reduction minimizes ash-related deposition, thereby improving operational stability and reducing maintenance requirements. These findings are particularly relevant in the Indonesian context, where decentralized biomass supply chains often result in variable fuel quality. Pre-treatment, therefore serves as a critical standardization step, enabling more seamless integration of biomass into existing coal-fired systems.

Despite the substantial reduction in CO_2 and SO_2 emissions observed in pre-treated co-firing blends, NO_x mitigation remains a key challenge. NO_x formation is strongly influenced by fuel-bound nitrogen, as evidenced in coffee husk and mangrove shells, which exhibit higher nitrogen content compared to W-SCS and WP. The interaction of fuel-bound nitrogen with high combustion temperatures promotes NO_x formation, limiting the effectiveness of pre-treatment strategies in reducing these emissions. This underscores the need for optimized combustion control strategies, including air staging and temperature management, to complement fuel pre-treatment.

These findings reveal a critical trade-off between CO_2 reduction and NO_x control, whereby strategies that enhance carbon efficiency and combustion completeness may not proportionally reduce nitrogen-derived emissions. Accordingly, biomass selection must account for both carbon and nitrogen content to achieve balanced environmental performance in co-firing systems.

These findings underscore the strategic role of pre-treated biomass in Indonesia's energy transition, simultaneously advancing SDG 2, 7, 8, 12, and 13 by promoting sustainable residue use, renewable energy deployment, rural economic growth, efficient resource valorization, and emission reduction. Aligned with RPJMN targets for 23% renewable energy by 2029 and Indonesia's 2060 carbon neutrality commitment, biomass co-firing with pre-treated feedstocks provides a cost-effective, scalable, and immediately deployable pathway to reduce emissions within existing coal-fired infrastructure, supporting a pragmatic transition to net-zero energy systems while ensuring energy security and operational reliability.

Conclusion

This study demonstrates that leaching and torrefaction markedly enhance the suitability of Indonesian biomass residues for co-firing with low-rank coal by improving fuel quality, increasing energy density, and imparting coal-like combustion characteristics, thereby boosting thermal efficiency, combustion stability, and reducing slagging and fouling risks. At co-firing ratios up to 30%, these treatments achieve substantial emission reductions, approximately 12% for CO_2 and 30% for SO_2, while NO_x emissions remain contingent on fuel nitrogen content and combustion conditions. By stabilizing heterogeneous biomass, this low-cost, scalable pre-treatment strategy not only ensures operational reliability but also aligns with Indonesia's energy transition, supports broader sustainable development objectives, and provides a pragmatic pathway towards carbon neutrality by 2060 through the integration of renewable biomass into existing coal-fired infrastructure.

Limitations

Despite the valuable insights provided, several limitations should be acknowledged. Firstly, the stoichiometric emission modelling approach offers a simplified representation of combustion processes and does not fully capture the complexity of real-world systems, particularly with respect to thermal and prompt NO_x formation mechanisms. As a result, the reported NO_x values primarily reflect fuel-bound nitrogen contributions and may not fully represent temperature-dependent reaction pathways.

Secondly, the slagging and fouling assessments are based on laboratory-scale analysis, which may not fully replicate the conditions encountered in industrial-scale boilers. Operational factors such as furnace design, residence time, and fuel mixing dynamics may significantly influence deposition behavior in practice. Finally, this study does not address the economic feasibility or long-term sustainability of biomass pre-treatment and large-scale co-firing deployment. Future research should therefore incorporate techno-economic analysis and supply chain optimization to ensure that proposed strategies are both economically viable and scalable within Indonesia's energy system.

Acknowledgments

The authors would like to thank the local biomass suppliers and processing facilities in Bandar Lampung, Indonesia, for their cooperation in providing the biomass samples. We also extend our sincere gratitude to the Lembaga Penelitian dan Pengabdian kepada Masyarakat (LPPM) Universitas Lampung for their financial support through the BLU funding, with contract agreement number 2022/UN26.21/PN/2025. Their contributions were essential for the successful completion of this research.

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